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Evaluation of electricity generation and energy cost of wind energy conversion systems in southern Algeria

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ABSTRACT

This paper presents the wind energy potential and economic analysis in five selected locations in the southern region of Algeria using wind speed data collected over a period of twelve years. The technical and economic evaluations of electricity generation from four commercial wind turbine models used for electricity generation located in these sites are examined. The wind speed data analysis shows that the sites located in the southern region of Algeria, except Tamanrasset, have a good wind potential for the wind energy development. The highest potential wind power was found at Adrar, with 88% of the time the wind speed is above 3 m/s. The yearly energy output, the capacity factor and the wind energy cost per unit of electricity generated by the selected wind turbines are calculated. In terms of energy production, the results show that Adrar is the best location for harnessing the wind power to generate electricity. The maximum energy output of 9429.8 MW h is found for Fuhrlander FL 2500 wind machine at Adrar. The capacity factor values are found to vary from a minimum of 13% at Tamanrasset and a maximum of 48% in Adrar. In addition, the results show that the minimum cost per kW h of electricity generated is found to be 0.01204 $/kW h for Suzlon S82/1.5MW wind turbine in Adrar, while the maximum value reaches 0.0923 $/kW h for the Fuhrlander FL 2500/901 in Tamanrasset. Among all the considered models, the Suzlon S82/1.5MW wind turbine is found to be the most attractive in terms of the cost per kW h. According to the obtained results, the wind resource appears to be suitable for power production in the southern region, which makes it a viable substitute to diesel oil for electricity generation.

Contents

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1. Introduction

Energy has been recognized as one of the essential inputs for social and economic development. Renewable energy is among the energy sources that are continually replenished.

These sources of energy are inexhaustible, clean and free. They offer many environmental and economical benefits in contrast to conventional energy sources. Wind energy is considered today as a cost effective energy and its technological advancements allow it to compete with conventional power generation technologies.

In Algeria, the electricity production is essentially based on fossil fuels in particular, natural gas which is abundant in the country. Since 2010, Algeria is implementing an ambitious strategy for encouraging and developing renewable energy in its territory (as the Plan for the Promotion of Renewable Energies, approved by the government on 03 February 2011 with the goal to generate 40% of total energy consumption from renewable sources by 2030 [1]). This strategy would gradually replace the use of fossil fuels (natural gas and oil) which currently are the main resource for the country's electricity generation, by other energy sources like solar and wind energy. The geographical location of Algeria has several advantages for extensive use of most of the renewable resources. In this regard, Algeria has to make use of its renewable resources, such as wind solar and geothermal, not only to meet the increasing energy demand but also for environmental reasons.

In this context, many renewable energy projects will be developed and realized to achieve this objective. One among these projects is the use of wind turbines to generate electricity. The starting point of any wind energy project is the resource assessment. It helps to identify suitable sites for wind turbines. The wind speed and its annual frequency are the critical parameters that determine the net output of wind turbine.

In this study, wind characteristic and wind energy potential in five locations of the southern region of Algeria were analyzed using the wind speed data collected during the period 1976–1988. In addition, the performance of selected commercial wind turbine models designed for electricity generation located in these sites are examined and economic evaluation of the wind energy in the selected sites is performed.

This study may provide information for developing wind energy sites and planning economical wind turbines capacity for the electricity production in Algeria.

2. Wind speed data and sites descriptions

The present study is based on a data source measured at a height of 10 m above ground level for five different sites located in the southern region of Algeria.

The wind speed data were collected during the period 1976–1988 with different collection periods for each site [2]. Fig. 1 shows the locations of these sites. The wind data for these meteorological stations were obtained from the Algerian Meteorological National Office. Table 1 shows the geographical coordinates of these stations and the period for which wind data were available for each station.

3. Analysis procedure

The Knowledge of the characteristics of the wind regimes in any locations is important in the exploitation of wind resources.

3.1. Wind speed frequency distribution

To evaluate the wind potential in any areas, the knowledge of the wind speed frequency distribution is a very important factor. The probability distribution of wind speeds is the key information needed to estimate wind energy output at a given site for a particular wind turbine generator. There are several probability

Fig. 1. Distribution of meteorological stations over Algeria.

Table 1
Geographical data for the selected stations.

Station	Coordinates			
	Latitude (deg.)	Longitude (deg.)	Altitude (m)	Period
Adrar	27°49′N	00°17′W	263	1977–1988
Bechar	31°37′N	02°14′W	811	1976–1988
Ghardaia	32°24′N	03°48′E	468	1978–1987
In Amenas	28°03′N	09°38′E	561	1977–1988
Tamanrasset	22°47′N	05°31′E	1377	1976–1988

density functions that can be used to describe the wind speed frequency distribution [3–6]. The Weibull distribution technique is widely accepted and used to estimate a site's probability distribution of wind speeds because it usually provides the best fit of measured wind data [7,8].

The Weibull probability density function is given by the following Eqs. [3,9–17]:

$$f_w(v) = (k/c)(v/c)^{k-1}\exp[-(v/c)^k] \tag{1}$$

where v is the wind speed, k is a dimensionless Weibull shape parameter, which is a measurement of the width of the distribution, and c is a Weibull scale parameter which is closely related to the mean wind speed.

The two parameters of Weibull can be determined by the mean wind speed-standard deviation method using the following equations [18,19]:

$$k = (\sigma/\overline{v})^{-1,0.86}, \quad 1 \le k \le 10 \tag{2}$$

$$c = \frac{\overline{v}}{\Gamma(1+1/k)} \tag{3}$$

where $\overline{v}$ is the mean wind speed and σ is the standard deviation. They are calculated using the following equations [19]:

$$\overline{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{4}$$

$$\sigma = \left[\frac{1}{N-1}\sum_{i=1}^{N}(v_i - \overline{v})^2\right]^{0.5} \tag{5}$$

where N is the data number.

The cumulative distribution function, $F(v)$, indicating the time fraction or probability that the wind speed v is smaller than or equal to a given wind speed v'

$$F(v) = P(v \le v') \tag{6}$$

Therefore, the cumulative distribution function is the integral of the Weibull probability density function, and is given by the following equation:

$$F(v) = 1 - \exp[-(v/c)^k] \tag{7}$$

3.2. Wind power density estimation

The wind power density evaluation is of fundamental importance in the assessment of wind power projects. The wind power density depends on the air density, the cube of the wind speed, and the wind speed frequency distribution. Therefore, this parameter is generally considered a better indicator of the wind resource than wind speed.

The mean wind power density is proportional to the mean cube of the wind speed, $\overline{v^3}$ and can be estimated by using the following equation:

$$\overline{P} = 0.5\ \rho\overline{v^3} \tag{8}$$

where ρ is the air density (usually taken as equal to 1.225 kg/m^3 for a temperature of 15 °C and a standard pressure of 1013 mb).

Two different ways can be used to estimate the wind power available at a given site.

First, based on the wind speed data and their distribution, the mean wind power density can be expressed as follows [20,21]:

$$\overline{P} = 0.5\ \rho\ \sum_{i=1}^{j}(v_i^3 \times f_i) \tag{9}$$

where v_i is the median wind speed of the ith class, f_i is the frequency of occurrence of winds in the ith class and j is the number of wind speed classes.

In terms of the Weibull parameters k and c, the mean wind power density may be also calculated by the following equation [8,16,22]:

$$\overline{P} = 0.5\rho\, c^3\, \Gamma\left(1+\frac{3}{k}\right) \tag{10}$$

3.3. Extrapolation of wind speed at different hub height

Wind speed increases with the height. In most cases, the available wind data are measured at height different from the hub height. Since the wind speed at the hub height is of interest for wind power application, the available wind speeds must be extrapolated to the wind turbine hub height. In this study, the power law is applied for this objective, as shown in the following equation [8,15,16,23,24,25]:

$$\frac{v}{v_o} = \left(\frac{h}{h_o}\right)^{\alpha} \tag{11}$$

where v is the wind speed at the required height h, v_o is the wind speed measured at the reference height h_o and α is the surface roughness coefficient and is assumed to be 0.143 (or 1/7) in most cases. The surface roughness coefficient can also be determined from the following expression [26–28]:

$$\alpha = \frac{[0.37 - 0.088\ \ln(v_o)]}{[1 - 0.088\ \ln(h_o/10)]} \tag{12}$$

Alternatively, the Weibull probability density function can be used to obtain the extrapolated values of wind speed at different heights. This approach is used in this study.

The Weibull parameters can be evaluated at any desired height, h, based on that at measurement height by the following equations [25–28]:

$$c(h) = c_o\left(\frac{h}{h_o}\right)^{n} \tag{13}$$

$$k(h) = k_o\frac{[1 - 0.088\ \ln(h_o/10)]}{[1 - 0.088\ \ln(h/10)]} \tag{14}$$

where c_o and k_o are the scale factor and shape parameter, respectively, at the measurement height, h_o, and h is the hub height. The exponent n is defined as [25]:

$$n = \frac{[0.37 - 0.088\ln(c_o)]}{[1 - 0.088\ln(h_o/10)]} \tag{15}$$

4. Estimation of wind turbine power and energy output

One of the major factors affecting the performance of a wind turbine is its power response to different wind speeds. This is usually given by the power curve of the turbine.

Different wind generators have different power output performance curves. Therefore, to simulate the electrical power output of a wind generator, different models are used [8,25,29–34]. Some authors [8,29–32] assume that the turbine power curve has a linear, quadratic or cubic form. Other authors [20,35] approximate the power curve with a piecewise linear function with a few nodes. In other case studies, a model which has a similar form is applied taking into account the Weibull parameters [36,37].

Some manufacturers provide a power curve in a tabular form for their wind turbine machines. However, in order to determine accurately the power generated by the wind turbine when the

wind speed is between two points j and $j+1$, an approximation method is necessary.

In this paper, the output power of the wind generator is estimated using an interpolation of the data values provided by the manufacturers. As the power curves are quite smooth, they can be approximated using a cubic spline interpolation [38].

The fitting equation of the output characteristic of wind generator can be expressed as [25]:

$$P_{wg}(v) = \begin{cases} 0 & v \le v_{ci}\ v \ge v_{co} \\ a_1 v^3 + b_1 v^2 + c_1 v + d_1 & v_{ci} < v < v_1 \\ a_2 v^3 + b_2 v^2 + c_2 v + d_2 & v_1 < v < v_2 \\ \cdots\cdots\cdots & \\ a_j v^3 + b_j v^2 + c_j v + d_j & v_{n-1} < v < v_r \\ P_r & v_r \le v < v_{co} \end{cases} \tag{16}$$

where $P_{wg}(v)$ is the wind generator power output at wind speed v, v_{ci} is the cut-in speed, v_{co} is the cut-out speed v_r is the rated speed and P_r is the rated power. The parameters a, b, c and d are the polynomial coefficients of the cubic spline interpolation functions, depending on the wind turbine model, and j is the number of cubic spline interpolation functions corresponding to $j+1$ value couples (speed, power) of data provided by the manufacturers.

The wind energy can be determined by the product of the power delivered by the wind generator at the wind speed, v, and the time, t for v prevails at the investigated site. The total energy generated by the wind generator over a period is calculated by adding up the energy output corresponding to all possible wind speeds in the related conditions, at which the system is operational. Thus, the energy output from a wind generator can be determined as follows [17]:

$$E_{wg} = \sum_{i=1}^{n} P_{wg}(v)\, t \tag{17}$$

where n is the number of hours in the period of the considered time, t is 1 h time duration (in this study, n=8760 and t=1).

The capacity factor, C_f, is the main performance parameters for the wind turbines. It is defined as the ratio of the energy actually produced by the system to the energy that could have been produced by it, if the machine would have operated at its rated power throughout the time period. The annual value of the capacity factor can be calculated as [39]:

$$C_f = \frac{E_{wg}}{E_{\text{rated}}} \tag{18}$$

5. Cost analysis

Since the economic viability of the wind energy projects depends on its ability to generate electricity at a low operating cost per unit energy, an accurate estimation of all the costs occurring over the life span of the system, is essential. Different methods are generally used to estimate the operating cost of a unit energy produced by the wind energy conversion system [40–42].

In this study, the estimation of the cost per unit is made by estimating the specific cost per kilowatt hour, which is expressed as the ratio of the accumulated net present value of all the costs, PVC, to the total energy produced by the system during the wind turbine lifetime [43–45].

The determination of the unit cost of energy involves two mains steps: In the first step, the PVC is calculated by taking into considerations the initial investment cost of the system and the present value of operations and maintenance cost throughout the lifetime system. The second step consists to determine the unit cost of energy (per kW h).

5.1. The present value of costs

The present value of costs (*PVC*) can be calculated as follows:

$$PVC = IC + C_{om(p)} \tag{19}$$

where *IC* is the initial investment cost, $C_{om(p)}$ is the present value of operation and maintenance costs during the system life

5.1.1. The initial investment cost

The initial investment cost of the wind turbine system consists of the wind turbine cost and all other initial costs including the costs of civil work, installation, connection cables to the grid and power conditioning.

The cost of the wind turbine can be determined as follows:

$$C_{wt} = C_{spe} P_r \tag{20}$$

where C_{spe} and P_r are, respectively, the specific cost and the rated power of the wind turbine.

The specific turbine cost is dependent on the rated power of the wind turbine but varies according to manufacturers [40,41,43]. We chose the specific turbine cost in considering three intervals (maximum and minimum values) as seen in Table 2 [40,41,45]. In this table, we note that the cost per kW decreases with the increase of the wind turbine size. For machine size above 200 kW, the turbine cost can be taken as 1150 $/kW (average value between a minimum of 700 $/kW and a maximum of 1600 $/kW).

The other initial costs are generally expressed as a percentage of the wind turbine cost. In this study, they are assumed to be 30% of the wind turbine cost.

5.1.2. The present value of maintenance cost

The present value of operation and maintenance costs (20 years of maintenance) of the wind turbines is expressed as

Table 2
Range of specific cost of wind turbines based on the rated power [40,41,43].

Wind turbine size (kW)	Specific cost ($/kW)	Average specific cost ($/kW)
< 20	2200–3000	2600
20–200	1250–2300	1775
200 >	700–1600	1150

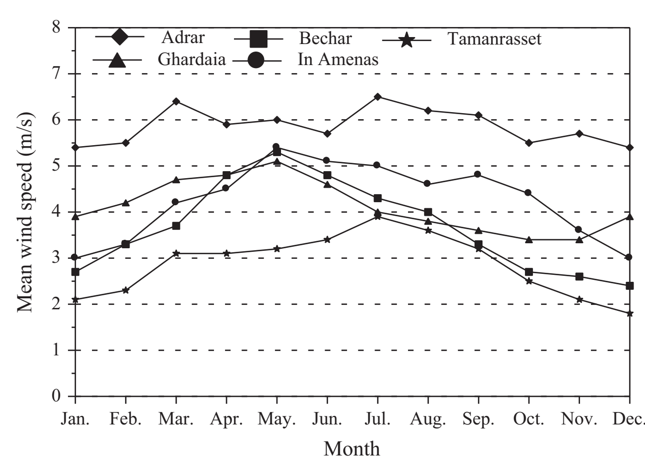

Fig. 2. Variation of the monthly average wind speed for the selected sites.

[6,21,46]:

$$C_{om(p)} = C_{oma}\left(\frac{1+i}{d-i}\right)\left(1-\left(\frac{1+i}{1+d}\right)^{T}\right), \quad d \neq i \tag{21}$$

where i, d and T are the inflation rate for operation, the interest rate and the useful lifetime of turbine in years (20 years), respectively.

C_{oma} is the operation and maintenance cost for the first year. This cost is expressed as a fraction of the component cost. In this study, it is assumed to be 25% of the annual cost of the turbine (machine price/life time) [7,44,45].

5.2. The unit cost of energy

Finally, the cost per kW h of electricity generation is computed can be determined. The following expression has been used to estimate the unit cost of energy (UCE) [39,24,47]:

$$UCE = \frac{PVC}{E_{wgt}}, \quad \frac{\$}{kW\,h} \tag{22}$$

where E_{wgt} represents the total energy generated by the wind turbine during its entire lifetime.

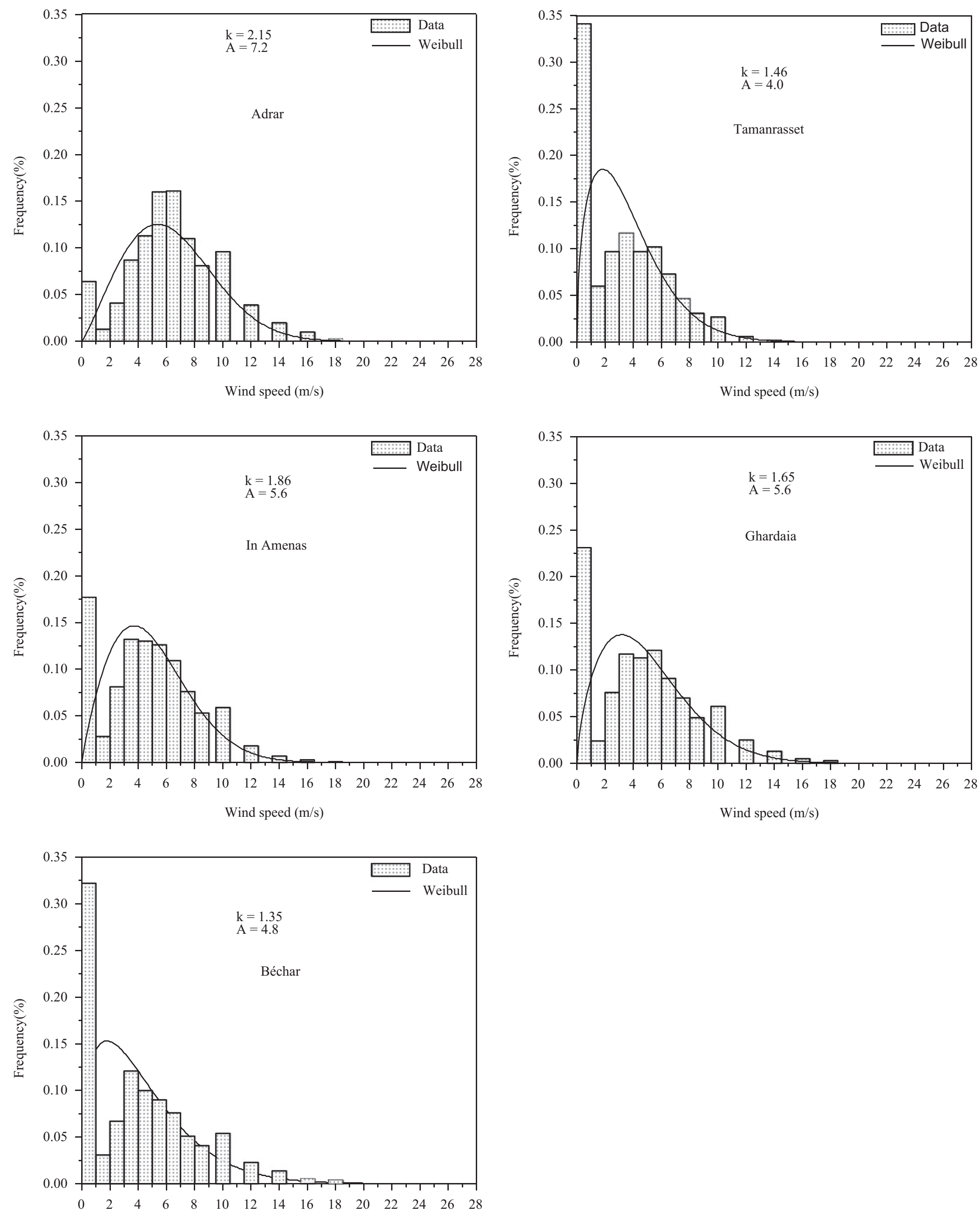

Fig. 3. Wind speed frequency with fitted Weibull distribution for different sites at 10 m height.

The cost estimation of the kW h of energy produced by the various wind turbine models has been done under the following assumptions [7,44,45,48]:

- The other initial costs including the costs of civil work, installation, connection cables
- to the grid and power conditioning are assumed to be 30% of the wind turbine cost
- The operation, maintenance and repair cost (C_{om}) was considered to be 25% of the annual cost of the wind turbine (machine price/lifetime).
- The interest rate (d) and inflation rate (i) were taken to be 8% and 6%, respectively.
- The machine lifetime (T) was assumed to be 20 years.

6. Results and discussion

The present study is based on a data source measured at a height of 10 m above ground level

for five different sites located in the southern region of Algeria. The wind data were collected during the period 1976–1988 and were obtained from the Algerian Meteorological National Office [2].

6.1. Wind characteristics

6.1.1. Monthly variation of the mean wind speed

The wind speed is one of the most important parameters in the wind profile of any given site.

The variations of the monthly mean wind speed at 10 m height are shown in Fig. 2.

The data analysis shows that in the southern region, except at Adrar and Tamanrasset, the monthly mean wind speed reaches its highest values during the period April to June. While the lowest monthly wind speed occurrs, at most sites, during the winter season.

As it can be seen from this figure, Adrar is the windiest site during all the year with an average annual wind speed around 6 m/s at 10 m above ground.

Also, the data analysis shows that the minimum mean wind speed in this region is observed in December at Tamanrasset with 1.80 m/s and the maximum one is about 6.50 m/s in July in Adrar.

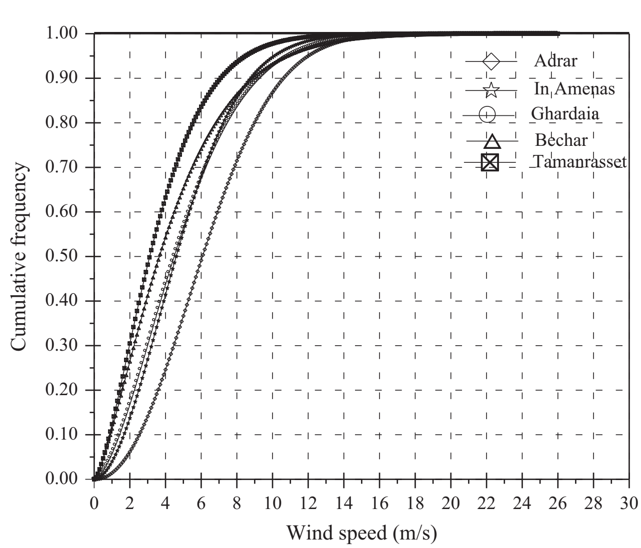

Fig. 4. Wind speed cumulative probability distributions for selected sites.

6.1.2. Wind speed frequency distribution and cumulative density distribution

In this study, the wind speeds were analyzed using the Weibull probability density function.

Fig. 3 shows the wind speed frequency histograms for the five sites over the data collection periods (Table 1) and the corresponding fitted Weibull functions.

As shown in Fig. 3, the Weibull distribution fits the observed distribution reasonably well in the relevant wind speed range, hence indicating that it describes the data adequately. Exception is made for the sites with high frequencies at low wind speeds. In this regard, the case of Tamanrasset and Bechar is noteworthy

Table 3
Weibull distribution parameters at 10 m height.

Location	10 m			70 m		
	V (m/s)	*k*	*C* (m/s)	*V* (m/s)	*k*	*C* (m/s)
Adrar	5.9	2.15	7.2	2.6	10.55	7.7
Bechar	3.6	1.35	4.8	1.6	7.54	4.7
Gharadaia	4.1	1.65	5.6	2.0	8.57	5.4
In Amenas	4.3	1.86	5.6	2.2	8.57	5.6
Tamanrasset	2.9	1.46	4.0	1.8	6.48	3.8

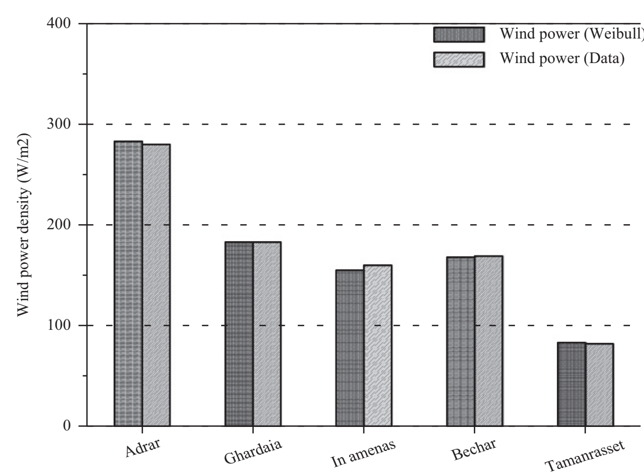

Fig. 5. Annual mean wind power density at 10 m height for different site.

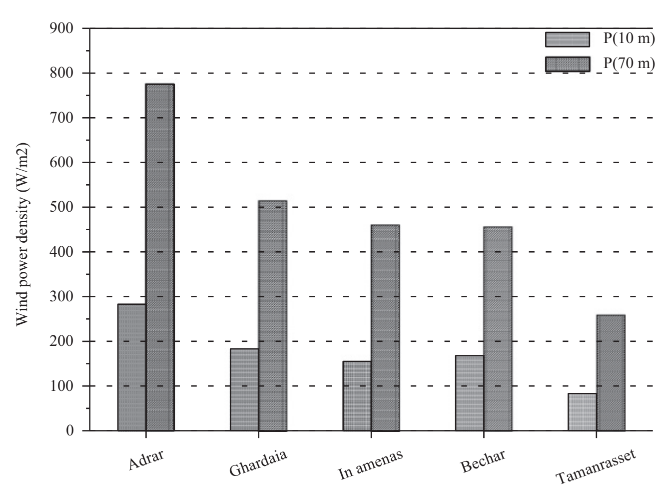

Fig. 6. Annual mean wind power density at the heights 10, 70 m for different sites.

where over 30% of the observations were between 0 and 1 m/s range.

On the basis of the observed wind speed frequency (Fig. 3) and by considering a typical wind machine with cut-in speed (3 m/s) and rated speed (13 m/s), some preliminary conclusions can be drawn:

- At Bechar, In Amenas and Gharadaia, about 55–75% of the wind speeds recorded lie between cut-in (3 m/s) and rated speed 13 m/s. This means that a typical wind turbine with the above specifications (3 m/s cut-in and 13 m/s rated) operates about 55–75% of the time at partial load.
- At Tamanrasset site about 50% of the wind speed recorded was less than 3 m/s. This effectively rules out this station for wind power utilization, as the wind machines would be at a standstill for a large portion of the time. While at Adrar site, only 12% of the wind speed recorded was less than 3 m/s. Therefore, the wind turbine installed on this site can produce energy for about 88% of the time with about 6% falling in the full power range (13 m/s to cut-out).

As the hub height exceeds 10 m (measured height), the wind turbines can operate for large wind speed intervals.

The cumulative probability distributions of the wind speeds for the selected locations obtained from the Weibull distribution functions are shown in Fig. 4.

The cumulative distribution function can be used for indicating the time fraction for which wind speed is within a certain speed interval. Therefore, the time for which a wind turbine could be functional in a given site can be estimated.

As seen in Fig. 4, the cumulative probability distributions of the wind speed show a similar trend.

For wind speeds less or equal to 3 m/s cut-in wind speed, Adrar, In Amenas, Ghardaia, Bechar and Tamanrasset have frequencies of about 12%, 29%, 33%, 42%, and 50%, respectively. This indicate that wind turbine system with cut-in wind speed of 3 m/s installed on the same locations, respectively can produce energy for about 88% , 71%, 67%, 58% and 50% of the time. If a wind turbine system with design cut-in wind speed of 4 m/s is used in these sites for electricity generation, this machine can generate energy for about 76%, 60%, 57%, 47%, and 38% of the time, respectively.

6.1.3. Wind power density

Using Eq. (9) and the wind speed distributions, the mean wind power density can be calculated for all the selected sites. Besides, the mean wind power density can be also estimated from the Weibull parameters (c and k) given in Table 3 by using Eq. (10).

Fig. 5 shows the mean wind power densities calculated from the frequency of occurrence of speed classes and those obtained from the Weibull parameters for all the sites.

The obtained results show that the estimation of the mean wind power density based on the Weibull parameters gives values very close to those calculated from the frequency of occurrence of speed classes. Consequently, the utilization of the Weibul parameters for the evaluation of wind energy potential may be adequate for these sites.

In addition, the wind power density can be estimated, at different heights, by using Eqs. (10), (13–15). Fig. 6 presents the mean wind power density at a height of 10 and 70 m from the ground for the selected sites.

The results show that the selected sites, except Tamanrasset, have an annual mean wind power density between 160–280 W/m^2 and 460–775 W/m^2 at the heights of 10 and 70 m, respectively. The highest values of mean wind power density of 280 W/m^2 and 775 W/m^2 at 10 and 70 m heights, respectively, are found at Adrar site. Consequently, this part of the country of Algeria has a good potential for developing wind energy sources, especially Adrar.

Tamnarasset has a low wind resources potential with a power density not exceeding 100 W/m^2 and 300 W/m^2 at the heights of 10 and 70 m that makes this site unfavorable location for the wind turbines installation for electricity generation.

In conclusion, it is interesting to note that:

- There is an important potential for wind energy exploitation in the southern region of Algeria, especially, Adrar.
- When the hub height increases from 10 to 70 m, the available wind power density increases by a factor of 3.

6.2. Performance of selected wind turbines

The following analysis is to help designers and users to choose the most suitable wind turbine.

For the wind turbine performance assessment in the five locations considered in this study, four commercial wind machine models (Vergnet GEV HP1MW, Suzlon S82/1.5MW, Vestas V90/2MW and Fuhrlander FL 2500) with different rated power are selected. The technical data of the selected wind turbine models is

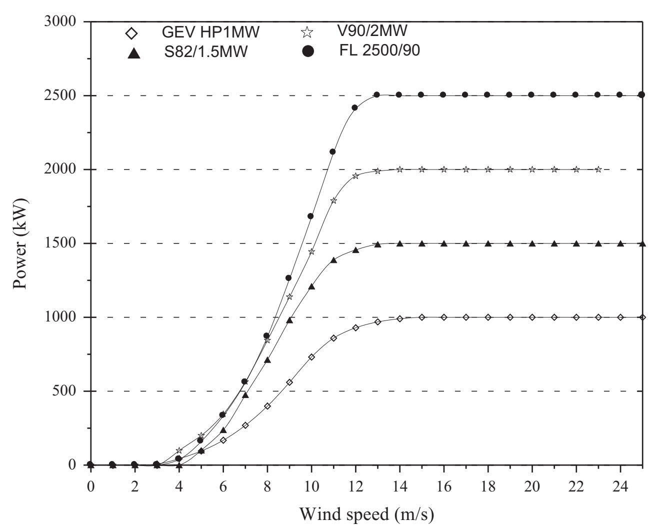

Fig. 7. Power curves for the selected wind turbines.

Table 4
Technical data of different commercial wind turbines used in the analysis [49–53].

Turbine model	Cut-in wind speed (m/s)	Cut-off wind speed (m/s)	Rated wind speed (m/s)	Rated power (kW)	Hub height (m)	Rotor diameter (m)	Swept area (m^2)
Vergnet GEV HP1MW	3	25	15	1000	70	62	3019
SuzlonS82/1.5MW	4	20	14	1500	70–78.5	82	5281
Vestas V90/2MW	4	23	14	2000	95–105	90	6362
Fuhrlander FL 2500/90	3.5–4	25	13	2500	85–160	90	6362

summarized in Table 4 [40–44]. The power curves for all the wind machines are shown in Fig. 7. For each location, the energy output and capacity factor are determined.

6.2.1. Annual energy output

Fig. 8 shows the simulation results of the annual energy output from the selected wind turbine models at all the locations considered in this study.

As shown in this figure, the annual energy output ranges from about 1107.86 MW h in Tamanrasset with the GEV HP1MW model to 9429.830 MW h in Adrar using the Fuhrlander FL 2500 wind machine.

Regardless of the location, the Fuhrlander FL 2500 wind turbine model generates the highest quantity of annual energy output while the Vergnet GEV HP 1MW model produces least energy amount. In addition, it can be observed that Adrar is the best location for harnessing the wind power to generate energy while Ghardaia is the second best location. Therefore, the maximum energy output from the other three wind machines (Vergnet GEV HP 1MW, Suzlon S82/1.5MW and Vestas V90/2MW), are obtained for Adrar. The annual energy output for this site ranges from 4002.30 MW h using Vergnet GEV HP 1 MW model to 9429.83 MW h using Fuhrlander FL 2500 wind machine.

The site of Tamanrasset has the least amount of annual energy. The annual energy varies between 1107.87 MW h using the Vergnet GEV HP 1MW model and 2347.23 MW h for the Fuhrlander FL 2500 one.

In the case of Suzlon S82/1.5MW model, the annual energy output ranges from 1695.39 MW h (Tamanrasset) to 6370.55 MW h (Adrar). While in the case of Vestas V90/2MW model, the generated annual wind energy in the considered stations varies between 2231.12 MW h in Tamanrasset to 8180.46 MW h in Adrar.

For the two other sites (In Amenas and Bechar), the annual energy output ranges from 1704.54 MW h to 3725.43 MW h and 1551.41 MW h to 3341.35 MW h for In Amenas and Bechar, respectively.

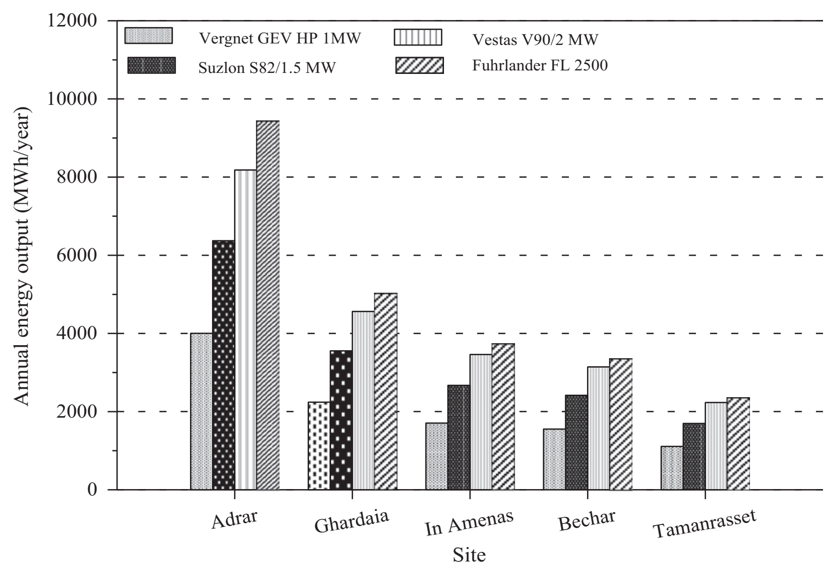

Fig. 8. Annual energy output from selected wind turbine models at the different sites.

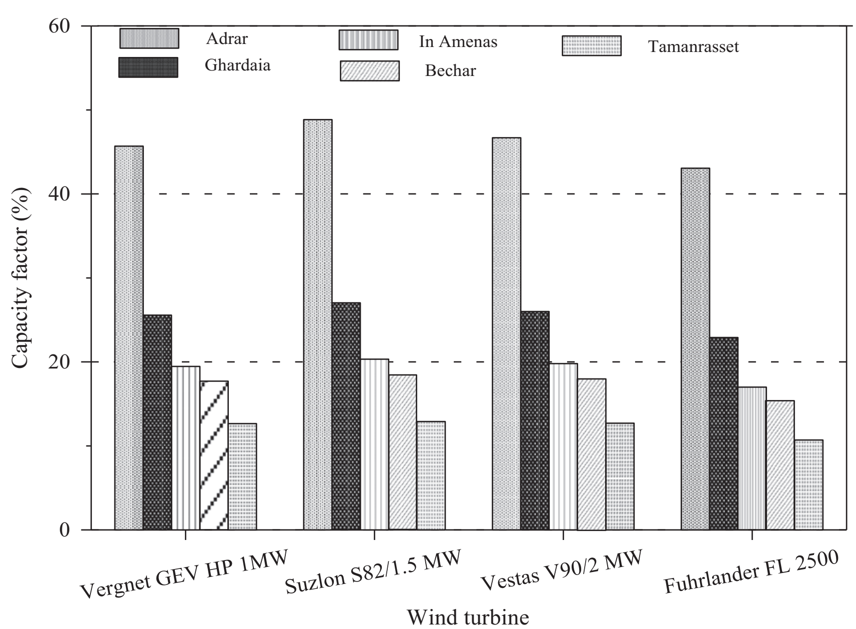

Fig. 9. Capacity factor for selected wind turbine models for different sites.

The site of In Amenas ranks third, among all the sites considered in this study, in wind energy production.

6.2.2. *Capacity factor*

Another way of stating the annual energy output from a wind turbine is to look at the capacity factor for the turbine in its particular location. The energy output is used to calculate the capacity factor of the wind machines.

The annual capacity factors calculated for the four wind turbines considered in this study are presented in Fig. 9. This figure shows that the capacity factor depends on the site and on the machine model. Therefore, the capacity factor of wind turbine varies greatly from one site to another. It can vary by a factor of two or more depending on site. While at a given site, this factor varies slightly from one turbine model to another.

The Suzlon S82/1.5MW model has the highest capacity factor with a value between 13% and 48% according to the site.

Furthermore, the Fuhrlander FL 2500/90 model has the least capacity factors for each site. The lowest value of capacity factor for this model is found to be 10% in Tamanrasset.

The capacity factors for Vergnet GEV HP 1MW and Vestas V90-2000 have almost the same values for all the sites. They were found to vary between 12% and 46%.

As shown in Fig. 9, the highest capacity factor of 48% is obtained for the site of Adrar using Suzlon S82/1.5MW. The capacity factors for this site were found to be between 36% and 48%. The site of Ghardaia is the second site while comparing the capacity factors with those of other sites. The lowest value of capacity factor is calculated as 10.7% for Fuhrlander FL 2500/90 model in Tamanrasset site. This means that this site may not be good site for wind energy development for electricity generation but small scale applications.

In addition, the Fig. 9 shows that Adrar and Ghardaia have capacity factors greater than the recommended minimum value of 25% for all wind turbines models. This also follows previous observation that Adrar and Ghardaia locations are excellent sites for wind energy development to be used for electricity production while In Amenas and Bechar are partially favourable. Based on the capacity factor of wind turbine models, the Suzlon S82/1.5MW model will be the best choice.

6.2.3. *Monthly energy output*

The monthly energy output for selected four wind turbine models (Vergnet GEV HP1MW, Suzlon S82/1.5MW, Vestas V90/2MW and Fuhrlander FL 2500/90) for all the sites are shown in Fig. 10.

Regardless of the wind turbine models, Adrar is the best location among the considered sites, for harnessing the wind power, to generate energy while Ghardaia is the second best location.

The maximum electricity production from all selected wind turbine models occurs in March and April for Adrar and May for the other sites, while the monthly minimum energy output from all selected models is obtained during the winter season (November, December, January).

The monthly energy output from the Vergnet GEV HP 1MW model varies from 12 MW h in January (Tamanrasset) to 400 MW h in March (Adrar).

For the Suzlon S82/1.5MW model, the monthly energy output is found to be between 12 MW h in January (Tamanrasset) and 630 MW h in March (Adrar).

Similarly the monthly energy output from the other two wind turbines Vestas V90/2MW and Fuhrlander FL 2500/90) ranges from 19.8 MW h in January (Tamanrasset) to 810 MW h in March (Adrar) and from 18.20 MW h in January (Tamanrasset) to 950 MW h in March (Adrar), respectively.

As can be seen in the Fig. 10, in almost all sites considered, the monthly energy production is relatively low during the period (November–February) compared to the energy produced in the other months. This is due to the wind potential quality at this period.

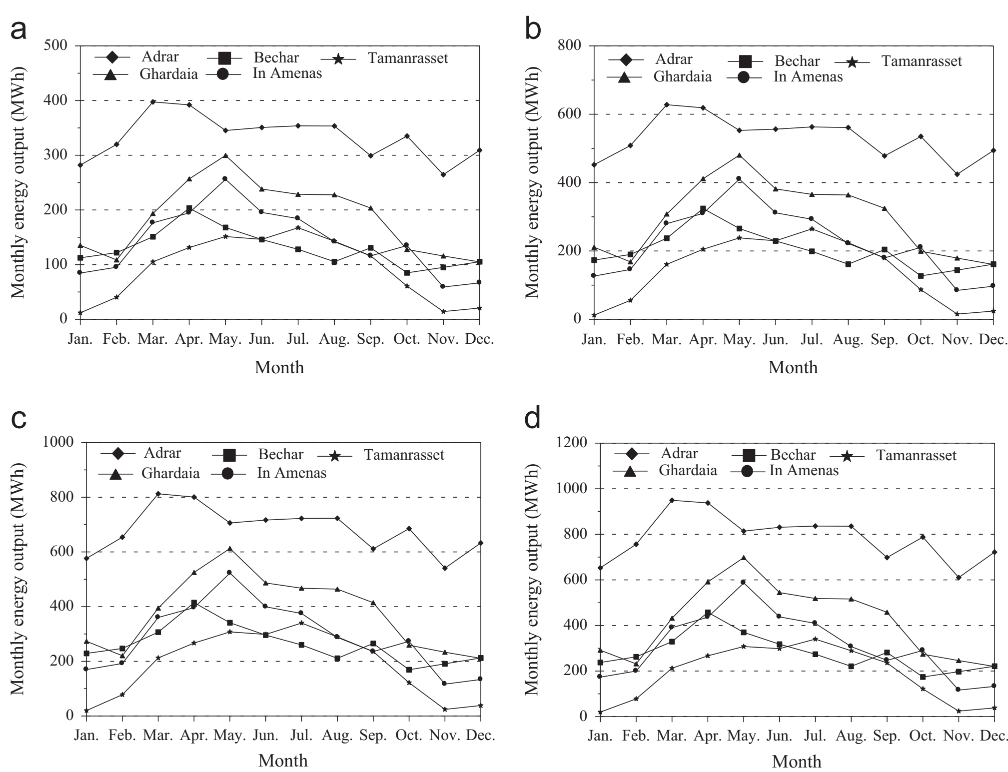

Fig. 10. Monthly energy output for selected wind turbine. (a) Vergnet GEV HP1MW, (b) Suzlon S82/1.5MW. (c) Vestas V90/2 MW and (d) Fuhrlander FL 2500/90.

6.3. Energy cost analysis

The economic analysis was carried out to estimate the cost of the kW h of energy produced by the various wind turbine models. The cost estimation has been done under the following assumptions [7,43,46]:

- The operation, maintenance and repair cost (C_{om}) was considered to be 25% of the annual cost of the wind turbine (machine price/lifetime).
- The interest rate (d) and inflation rate (i) were taken to be 8% and 6%, respectively.
- The wind turbine lifetime (T) was assumed to be 20 years.
- The other initial costs including the costs of civil work, installation, connection cables to the grid and power conditioning are assumed to be 30% of the wind turbine cost

The results of the cost analysis are presented in Table 5.
According to the cost analysis it is seen that:

- In the southern region of country, the cost of electricity per kW h produced using the Fuhrlander FL 2500/90 model varies between a minimum of 0.0230 $/kW h at Adrar and a maximum of 0.0923 $/kW h at Tamanrasset.
- Using the Vestas V90/2MW wind turbine, the cost of electricity produced varies between a minimum of 0.0212 $/kW h and a maximum of 0.0777 $/kW h corresponding to Adrar and Tamanrasset, respectively.
- The cost of electricity produced using the Suzlon S82/1.5MW and GEV HP1MW wind turbines were found to vary from 0.0204 to 0.0766 $/kW h and 0.0216 to 0.0782 $/kW h, respectively.
- The least cost of unit energy per kW h produced by each wind turbine is obtained for Adrar. While the highest cost per kW h of energy is obtained for Tamanrasset.
- For all the sites, the minimum cost per kW h of energy is obtained with Suzlon S82/1.5MW model.

Table 5
Cost analysis for selected wind turbines ($/kW h).

Site	Turbine model	Yearly energy (MW h/year)	Capacity factor	Cost per unit ($/kW h)
Adrar	Vergnet GEV HP1MW	4002.3	0.4569	0.0216
	Suzlon S82/1500	6370.5	0.4848	**0.0204**
	Vestas V90/2MW	8180.5	0.4669	0.0212
	Fuhrlander FL 2500/90	9429.8	0.4306	0.0230
Ghardaia	Vergnet GEV HP1MW	2239.8	0.2557	0.0387
	Suzlon S82/1500	3552.0	0.2703	**0.0366**
	Vestas V90/2MW	4560.6	0.2603	0.0380
	Fuhrlander FL 2500/90	5019.4	0.2292	0.0431
In Amenasr	Vergnet GEV HP1MW	1704.5	0.1946	0.0508
	Suzlon S82/1500	2669.9	0.2032	**0.0487**
	Vestas V90/2MW	3460.4	0.1975	0.0501
	Fuhrlander FL 2500/90	3725.4	0.1701	0.0581
Bechar	Vergnet GEV HP1MW	1551.4	0.1771	0.0558
	Suzlon S82/1500	2415.1	0.1838	**0.0538**
	Vestas V90/2MW	3141.7	0.1793	0.0552
	Fuhrlander FL 2500/90	3341.3	0.1526	0.0648
Tamanrasset	Vergnet GEV HP1MW	1107.9	0.1265	0.0782
	Suzlon S82/1500	1695.4	0.1290	**0.0766**
	Vestas V90/2MW	2231.1	0.1273	0.0777
	Fuhrlander FL 2500/90	2347.2	0.1072	0.0923

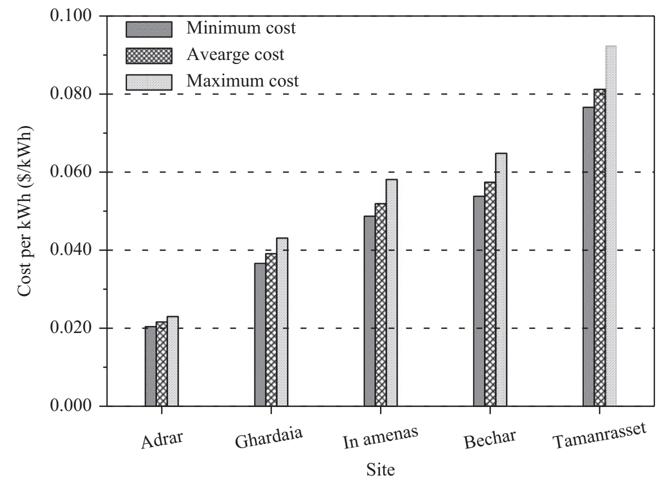

Fig. 11. Cost of the electricity produced by the most efficient wind turbine (Suzlon), by the less efficient one (Fuhrlander) and the average cost in each location.

- The cost per kW h of energy produced depends on the wind turbine model as well as the site wind characteristics (represented by the turbine capacity factor).
- In all sites considered, except Tamanrasset, the electricity generation cost per kW h from wind machines does not exceed 0.060 $/kW h which is a very competitive price compared to the price of electricity paid by the consumer of domestic sector in Algeria (0.054 $/kW h). This cost will be decreased further as the costs of wind energy systems will be lowered based on the development of wind energy technology.

The important result derived from the current study encourages the construction of wind farms in the southern region especially Adrar for electricity generation. In addition, the usage of the wind turbine model “Suzlon S82/1.5MW is highly recommended.

Fig. 11 gives the cost of the electricity produced by the most efficient wind turbine (Suzlon), by the less efficient one (Fuhrlander) and the average cost in each location.

As can be seen from the Fig. 11, the minimum cost per kW h of energy found does not exceed 0.060 $/kW h at all sites, except Tamanrasset where the cost of producing electricity per kW h is found to be 0.0766 $/kW h. The minimum cost of 0.0204 $/kW h is obtained for Adrar using Suzlon S82/1.5MW model. The site of Ghardaia is the second best site with 0.0366 $/kW h.

Moreover, it can be inferred that the unit energy cost depends more on the site than on the wind turbine model; thus, the average cost per kW h in Tamanrasset is about three times higher than in Adrar.

7. Conclusion

In this study, the wind energy potential and economic analysis in five locations in the southern of Algeria were investigated. In addition, The performances of selected commercial wind turbine models used for electricity generation located in these sites were examined. The following conclusions can be drawn from the results of the present study:

- The sites located in the southern region, except Tamanrasset, have an important potential for wind energy exploitation
- The highest values of mean wind power density of 280 and 775 W/m^2 at 10 and 70 m heights, respectively are found at

Adrar, while the lowest values are obtained in Tamanrasset as 100 W/m^2 and 300 W/m^2 at the heights of 10 m and 70 m, respectively.
- Increasing the hub height from 10 to 70 m increases the available wind power density by a factor of 3.
- In terms of energy production and capacity factor, Adrar is the best location among the considered sites, for harnessing the wind power to generate energy while Ghardaia is the second best location. The maximum energy output of 9429.8 MW h is found for Fuhrlander FL 2500 wind machine at Adrar.
- The Suzlon S82/1.5MW model has the highest capacity factor value among the models considered for all the sites. The capacity factor values for this wind machine model were found to vary between 13% and 48% for the sites considered in this study.

According to the cost analysis, it is seen that:

- The unit cost of energy varies between 0.0204 $/kW h for Suzlon S82/1.5MW wind turbine in Adrar and 0.0923 $/kW h for Fuhrlander FL 2500/901 in Tamanrasset.
- The minimum cost per kW h of electricity generated from the wind turbines considered in this study, is found to be 0.0204 $/kW h at Adrar.
- The electricity generation cost per kW h from wind turbines in almost all sites considered is very competitive price compared to the price of electricity paid by the consumer of domestic sector in Algeria.
- The Suzlon S82/1.5MW wind turbine among all the models considered in this study for same hub heights (70 m) is the most attractive in terms of the cost per kW h.
- The wind resource appears to be suitable for power production on the south of the country and it could provide a viable substitute to diesel oil for electricity generation.

Finally, The Suzlon S82/1.5MW wind turbine model is recommended for wind farms constructing at the southern region especially Adrar for electricity generation.

This work should be extended to study the wind energy at different locations; this will help to identify the most favorable areas for wind development in Algeria.

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